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STUDIES OF FRICTION AND WEAR CHARACTERISTICS OF VARIOUS WIRES FOR WIRE-BRUSH SKIDS

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16. Abstract

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In general, the friction coefficient developed by the candidate wires was found to be independent of bearing pressure and ranged between 0.4 and 0.6 under the test conditions of this investigation. The friction coefficient was not degraded when the surface was wetted and appears to be independent of wire diameter except perhaps when wire size is relatively large compared with the surface asperities. Generally, the high friction demonstrated by the soft materials was accompanied by high wear rates; conversely, the hard materials provided greater wear resistance but offered lower friction. For all test wires, the wear was shown to increase with increasing bearing pressure and, in general, for the same bearing pressure, wear increased with increasing wire diameter and decreased when the surface was wetted.

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SUMMARY

An experimental investigation was conducted to examine under laboratory conditions the friction and wear characteristics of 22 types and sizes of wires for potential use in wire-brush skids. These characteristics were determined by placing brushes made from candidate wires on a belt sander whose moving belt simulated landing roll-out distance. At the same time, the drag force and wear behavior were monitored. Data were obtained over distances up to 3048 m (10 000 ft) at preselected bearing pressures of 172 to 1034 kPa (25 to 150 psi).

In general, the friction coefficient developed by the candidate wires was found to be independent of bearing pressure and ranged between 0.4 and 0.6 under the test conditions of this investigation. The friction coefficient was not degraded when the surface was wetted and appears to be independent of wire diameter except perhaps when wire size is relatively large compared with the surface asperities. Generally, the high friction demonstrated by the soft materials was accompanied by high wear rates; conversely, the hard materials provided greater wear resistance but offered lower friction. For all test wires, the wear was shown to increase with increasing bearing pressure and, in general, for the same bearing pressure, wear increased with increasing wire diameter and decreased when the surface was wetted.

INTRODUCTION

A landing-gear system must be designed to provide airplane directional stability and control while the vehicle is on the ground. The system must also be able to stop the aircraft within a reasonable distance under various runway conditions. Antiskid braking systems are installed on most commercial and military airplanes, but flight-test and field experiences have shown that the performance of these systems can be degraded when the runway becomes slippery. This degradation can result in reduced airplane stability and dangerously long roll-out distances during landing. In addition, the conventional braked wheel with a rubber tire must absorb larger amounts of energy as the weight and landing speed of aircraft increase and as the landing-gear system approaches its physical limit. Research programs to improve both the antiskid systems and braking capability of aircraft have indicated a need to explore new braking concepts capable of assuring both adequate braking and airplane stability during ground operations regardless of runway surface conditions.

One promising concept is a combination wheel and skid gear such as that illustrated in figure 1. Here, a hydraulically actuated wire-brush skid is

mounted between the wheels of a 4-wheel bogey landing gear to replace the conventional brake system. This concept was derived from a reconsideration of research conducted in the early sixties by NASA (ref. 1) and others (refs. 2 to 5) on the use of various skid materials as the main landing gear of a reentry vehicle. Those studies showed that some of the materials, notably the wire-brush skid, developed a high level of friction which was essentially unaffected by forward speed and runway surface condition. This concept combines the desirable drag-producing characteristics of a wire-brush skid under all weather conditions with the advantages of a rubber tire for energy absorption during landing impact, ride cushioning, directional stability, and for maneuvering the vehicle in and around the terminal area. The braking effort, which is directly proportional to the vertical force applied to the skid-runway interface, is controlled by a pilot-operated metering valve. Thus, differential braking for heading changes is possible, and the freely rolling tires, although operating under reduced vertical load, would provide sufficient cornering force for directional stability.

For the wheel-skid concept to be appropriate to present and future aircraft and to keep skid size reasonable, the skids must operate at bearing pressures higher than those tested in reference 1 (152 kPa (22 psi) the maximum pressure tested). The skids must also have good wear-resistant properties, develop a satisfactory friction coefficient regardless of runway surface condition, be weight competitive, and cause minimum runway surface damage. With these criteria in mind, a laboratory screening investigation was conducted on various wire materials to study their potential for use in wire brush skids. This screening was done with small wire brushes to determine the feasibility of higher bearing pressure from a material standpoint, to establish the friction coefficient and wear for the various materials, and to form a basis for judging directions of large-scale studies. For the purposes of this investigation, twenty-two candidate wire specimens were loaded to bearing pressures ranging between 172 and 1034 kPa (25 and 150 psi) on a horizontal belt sander, and measurements were made of the relative friction and wear characteristics at constant velocity over simulated landing roll-out distances up to 3048 m (10 000 ft). This paper presents the results of that investigation.

SYMBOLS

Measurements and calculations were made in U.S. Customary Units. Values are presented in both SI and U.S. Customary Units.

A skid contact area, cm^2 (in^2)

F vertical load on skid, N (lbf)

g gravitational constant, 9.814 m/sec^2 (32.2 ft/sec^2)

I wire wear index, $\frac{cm^3}{cm^2}\Big/m$ $\left(\frac{in^3}{in^2}\Big/ft\right)$

L skid wear (eroded mass), kg (lbm)

l airplane stopping distance, km (ft)

m airplane mass, kg (lbm)

V airplane ground speed, knots (1 knot = 0.51 m/sec)

μ drag friction coefficient

ρ wire density, kg/m^3 (lbm/in^3)

Abbreviations:

a.d. as drawn

h.t. heat treated

w.w. weld wire

TEST SPECIMENS

In this study, tests were conducted on 22 different types and sizes of wire formed into small wire brushes. Wire selection was based on availability and information obtained from several wire manufacturing companies regarding hardness, tensile strength, and high-temperature use. The brushes were made by inserting a number of wires into an aluminum tube with a 3.45-mm (0.136-in.) inside diameter; the tube was then crimped to hold the wires firmly in place. The number of wires used in each brush varied depending on wire size, and the free end or trim length of the brushes was 5.08 cm (2.00 in.). Five brushes were constructed from each type of wire. Pertinent information describing the wire and the brushes is given in tables I and II. Table I lists the diameter and density of the wires, the number of wires per brush, and the total brush contact area (the net cross-sectional area). The test brushes included six sizes of music wire, weld wire, and spring wire from different materials (some of which were heat treated); two sizes of wire rope; and wire from a standard steel cleaning-wheel brush. The wire rope I brushes consisted of commercial steel cable 0.32 cm (0.125 in.) in diameter. The wire rope II brushes consisted of one strand (of seven) of commercial steel cable 0.95 cm (0.375 in.) in diameter. The rocket wire brush consisted of a carbon steel wire of extremely high tensile strength developed by a metal and wire company. The number of wires in each brush varied from 1 to 133, depending on the wire diameter which ranged from 0.25 to 2.16 mm (0.010 to 0.085 in.). There is little difference among the densities of the different wire materials. A description of the wires and the heat treatment where applicable is given in table II. A photograph of several brushes after testing is shown in figure 2.

APPARATUS AND INSTRUMENTATION

A photograph of the apparatus used in this study is presented in figure 3. The two primary components are identified in the figure: a belt sander used to simulate a runway surface and a force beam to measure the drag force developed between the brush and the belt surface. The sander was equipped with either a standard No. 60 grit aluminum oxide belt or a wet-dry belt, 10 by 133 cm (4 by

52 1/2 in.). The sander was operated at a constant surface speed. The force beam to which the test brush was attached measured the drag force, was counterbalanced to give zero load on the brush, and was free to pivot about a horizontal axis perpendicular to the direction of motion of the belt. Small weights were added around the body of the brush to produce the desired bearing pressures. The output of the force beam strain gage was recorded on an oscillograph; later, the output was reduced to a drag force and was divided by the vertical load on the brush to yield the friction coefficient.

TEST PROCEDURE

The test procedure consisted of placing each brush on, and perpendicular to, the moving belt surface under a preselected bearing load. The brush friction and wear characteristics were then monitored. The developed friction was continuously measured, whereas the extent of wear was periodically determined by measuring the brush trim length at sliding distance intervals of 610 m (2000 ft). A test was concluded when the total sliding distance of 3048 m (10 000 ft) had been reached or when the trim length of the brush had been reduced to approximately 0.64 cm (0.25 in.) from the original length of 5.08 cm (2.00 in.). The brush followed the same belt track for the entire distance. A new brush and belt track were used for each bearing pressure. Limited tests were made with a wet sanding belt surface to determine the effect of surface wetness on friction coefficient and wear. For these tests a stream of water was directed onto a wet-dry belt in front of the test brush.

All tests were made with the sander belt running at a constant surface speed of 34 knots (39 mph). Appropriate weights were added to each brush so that bearing pressures of 172, 345, 517, 689, and 1034 kPa (25, 50, 75, 100, and 150 psi) were obtained. Bearing pressure was calculated by dividing the vertical load on the brushes by the total area of the ends of the wires in contact with the belt surface.

RESULTS AND DISCUSSION

A value for the drag friction coefficient and a wear index were determined for each wire brush under each loading condition. The friction coefficient was obtained when the drag force developed between the brush and the belt surface was divided by the vertical load applied to each brush. Because of the elasticity of the wire brushes, the drag force fluctuated in a "stick-slip" manner and necessitated fairing the time histories of the drag force to obtain an average value. A wear index was obtained for each brush by relating brush wear to sliding distance. The following sections discuss the friction coefficients and wear indexes obtained with the brushes over the test range of bearing pressures.

Friction Coefficient

Bearing pressure, brush wire diameter, and surface wetness affect the friction coefficient developed by the various test brushes. (See figs. 4 and 5.)

Bearing pressure.- In view of the large number of different brushes, data which describe the variation of friction coefficient with bearing pressure are divided into three figures for the convenience of the reader: figure 4(a), all brushes fabricated from music wire; figure 4(b), all brushes constructed of wire 0.76 mm (0.030 in.) in diameter; and figure 4(c), the remaining brushes. The data for each brush are faired by a straight line which, with few exceptions, defines the trend of the relationship between these two parameters. The figure shows that except for the two largest sizes of music wire (fig. 4(a)), the developed friction coefficients ranged between 0.4 and 0.6. This range agrees well with the full-scale tests of the 5.08-cm (2.00-in.) wire brush presented in reference 1. The figure further shows that the friction coefficient for a given brush is generally insensitive to changes in the bearing pressure or gradually increases with increasing bearing pressure. The exceptions to the general trend are the two wire rope brushes whose friction coefficients are shown to increase appreciably with increasing bearing pressure (fig. 4(c)). This increase may be attributed to the relatively soft steel used in these brushes, where at the higher bearing pressures, friction is increased at the expense of increased wear, a condition which is discussed in a later section.

In an effort to rank the test brushes in terms of drag friction coefficient, the faired values at a bearing pressure of 689 kPa (100 psi) are presented in table III. Of the materials examined, heat-treated beryllium copper developed the highest friction level, and the two large diameter music wires developed the lowest.

Wire diameter.- Table III and figure 4(a) permit an evaluation of the effect of wire diameter on friction coefficient because they present the data from the tests of the six sizes of music wire. For wire diameters between 0.33 and 1.07 mm (0.013 and 0.042 in.), values for the friction coefficient extended over the narrow range between 0.45 and 0.48. The two larger sizes of music wire, with diameters of 1.93 and 2.16 mm (0.076 and 0.085 in.), developed friction coefficients roughly 25 percent lower. This lower friction level may be attributed to fewer contact points between the larger wire sizes and the belt surface since, on a relative scale, the large wires tend to be like a flat plate skid.

Surface wetness.- The effect of surface wetness on the friction coefficient is shown in figure 5, which presents the data obtained with brushes made of 17-7 PH stainless steel, h.t., II wire 0.76 mm (0.030 in.) in diameter. This wire was tested both dry and wet on a No. 60 carborundum grit wet-dry belt at various bearing pressures. The data indicate that friction coefficient is not degraded by a wet surface. In fact, values for friction coefficients obtained on the wet belt surface were slightly higher than those obtained on the dry belt surface, a result, perhaps, of the cooling effect of the water which reduced structural losses in the wire due to heat. The level of friction coefficient obtained with this brush on the dry surface is slightly lower than that noted during the regular test program (see fig. 4(b)) and is probably due to differences between the standard sanding belt and the wet-dry belt used for these tests.

Although the friction coefficients obtained in this investigation fall in the range of average coefficients developed by an antiskid braked wheel with rubber tire on a dry surface, they were obtained at a relatively low ground speed.

In addition, it is not known how the roughness of the sanding belt surface compares with that of a typical runway.

Wear

A wear index was determined for each brush at the various test bearing pressures from curves similar to those presented in figure 6. This figure shows the cumulative brush length wear at intervals of 610 m (2000 ft) over a total sliding distance of 3048 m (10 000 ft) for the 17-7 PH stainless steel, h.t., II wire brushes 0.76 mm (0.030 in.) in diameter. The slope of curves such as these describes the length of brush wear per unit sliding distance. However, direct comparison of wear with other brushes is not possible since the contact area was not the same - the area depended upon wire diameter and number of wires in each brush. To permit comparisons of brushes, the wear index, which is the ratio of the volume of brush material removed to the brush cross-sectional (contact) area per unit sliding distance, was derived for each brush. The weight of brush material removed per unit area is obtained by multiplying the wear index by the wire densities listed in table I. A comparison of the wearability of the various test brushes may be obtained from table IV which presents in ascending order the wear indexes of the brushes obtained under a bearing pressure of 689 kPa (100 psi). A lower wear index number identifies a more wear-resistant brush; thus, of the materials examined, René 41 demonstrated the best wear characteristics, and the soft beryllium copper and the wire ropes demonstrated the worst.

A comparison of the wear data of table IV with the friction data of table III shows no direct correlation between wear and friction. However, in general, hard materials provide good wear resistance, but they achieve this resistance at the expense of lower friction; soft materials demonstrate the opposite behavior characteristics.

Bearing pressure.- The effect of bearing pressure on the wear of each test brush is shown by the bar graph of figure 7. The wear index understandably increases with increasing bearing pressure for all brushes tested, but the relationship is not necessarily a linear one. The wear at the high bearing pressures is undoubtedly influenced by the high temperatures developed at the contact surfaces. Some of the brushes glowed red and were discolored after testing. The brushes exhibiting the lower wear indexes were those containing wires which tend to retain their mechanical properties at elevated temperatures. For example, René 41, which provided the lowest index, is recommended by wire manufacturers for high-temperature spring use in the 590° to 815° C (1100° to 1500° F) range. Heat treating the wires appears to reduce the wear index at higher bearing pressures as shown by the data for the A-286 and 17-7 PH stainless steel brushes. The incomplete wear data for the A-286 a.d. and beryllium copper brushes at the highest test bearing pressure were caused primarily by wire fatigue. The rapid fore-and-aft deflection of the brush during the "stick-slip" behavior evidently fatigued some of the wires until they failed at the base of the brushes. However, the greatest wear occurred with the wire rope I brush at a bearing pressure of 1034 kPa (150 psi). Such wear is attributed to the low column strength of that material. Under the high loadings of the wire rope I brush, wear occurred along the length of the leading wires rather than at their ends.

Wire diameter.- An indication of the effect of wire diameter on brush wear is shown in bar graph form in figure 8. The data were obtained from tests with brushes constructed from music wire of different diameters at several bearing pressures. The figure shows that, in general, wear increases with increasing wire diameter. The greater wear exhibited by the 0.33-mm (0.013-in.) wire brush at a bearing pressure of 1034 kPa (150 psi) can be attributed, in part, to its low column strength. As in the case of the wire rope I brush, this brush deflected an appreciable amount at the high bearing pressure and thus forced most of the wear to occur along the length of the leading wires. The figure also shows that brush wear increases with increasing bearing pressure.

Surface wetness.- The effect of a wetted surface on the wear of 17-7 PH stainless steel, h.t., II wire brushes 0.76 mm (0.030 in.) in diameter is shown in figure 9. This figure presents in bar graph form the results from tests made at five bearing pressures on both a dry and a wet belt surface. The figure shows that, at each bearing pressure, brush wear was less on the wet than on the dry surface. The lower wear on the wet surface is attributed to lower brush temperatures caused by the presence of water in the contact area.

Application of Results

The friction and wear data of this investigation have been applied to calculate skid requirements necessary to brake to a stop an airplane having an initial ground speed of 180 knots. The friction and wear data obtained with the various materials in the investigation at 34 knots with small brush areas on a belt sander may not be accurate for full size skids used at 180 knots on a runway surface, but the two situations are comparable. The results of this application are presented in figure 10. The stopping distance and the brush mass loss per unit area have been identified for skids built from the different types of wires operating on a surface similar to that of the belt sander at a constant bearing pressure of 689 kPa (100 psi). Thus, the friction coefficients of table III and the wear indexes of table IV are appropriate.

The stopping distances l noted in the figure disregard aerodynamic drag effects and were computed from the expression $l = V^2/2g\mu$ where V is the initial ground speed, g is the gravitational constant, and μ is the friction coefficient. This expression assumes that the total mass of the airplane is supported by the skid(s) and that the friction coefficient is constant with speed. The limited wire-brush data of reference 1 make this seem a reasonable assumption. The product of the stopping distance, the respective wear index, and the density associated with each wire brush yields the mass of brush material per unit contact area necessary to support the landing. The data of figure 10 indicate that generally the shorter stopping distances are obtained at the expense of skid material. Note that the mass loss was roughly the same for many of the materials tested. Again, brushes showing the least amount of wear were fabricated from wires suitable for application at high temperature. However, these wires are usually more costly. For example, advertised costs of 17-7 PH stainless steel, A-286, inconel X-750, and René 41 wire are 1 1/2, 3, 7, and 22 times, respectively, that of AISI type 302 stainless steel wire.

Further examples of applying the results from this investigation to an airplane are presented in figures 11 and 12. These figures provide the stopping distances of a 90 720-kg (200 000-lbm) airplane which commences braking at 180 knots, together with the contact area (fig. 11) or bearing pressure (fig. 12) and the wear of a skid to accommodate those distances, all as a function of the skid vertical loading. For these examples, 17-7 PH stainless steel, h.t. wire 0.76 mm (0.030 in.) in diameter was chosen because of its combined low mass loss and relatively short stopping distance (see fig. 10). Again, aerodynamic drag effects are disregarded, and the friction coefficient developed between the skid and the surface (assumed to be like that of the belt sander) is considered to remain constant with speed.

Fixed skid bearing pressure.- For the data presented in figure 11, the bearing pressure of the skid was maintained at 689 kPa (100 psi), but since the vertical load on the skid varied, the size of the skid (skid contact area) varied proportionally. Also, the expression for stopping distance must be written to account for the difference between the airplane mass m and the skid loading F. This expression becomes $l = mV^2/2g\mu F$. Once the stopping distance has been computed, the skid wear (eroded mass) L can be calculated from the material wear index I, the material density ρ, and the skid contact area A by the relationship $L = I\rho lA$. The figure shows that the mass of skid material required to support the braking effort is independent of the vertical loading on the skid since the contact area is forced to vary directly with the loading. However, the figure also shows that the stopping distance increases rapidly with decreased loading; thus, in selecting a skid for braking purposes, a compromise must be made between the desired stopping distance and the available space within the aircraft to house the skid.

Fixed skid area.- The data of figure 12 result from similar calculations, but in this example, the skid area is fixed at 0.77 m^2 (1200 in^2) and the bearing pressure increases directly with the vertical load applied to the skid. This example is a more realistic application of skids as brakes in a combination wheel-skid gear. Whereas the friction coefficient and wear index shown in figure 11 remained constant for all vertical loadings (since the bearing pressure was held fixed), both of these quantities varied in this example according to the data of figures 4(b) and 7. Figure 12 shows again that the skid wear in mass or volume is essentially independent of the vertical load and that the stopping distance increases rapidly when that load decreases. For example, with the skid supporting 30 percent of the airplane mass, the skid bearing pressure is 345 kPa (50 psi), but the stopping distance is roughly 2.9 km (9600 ft). However, with the skid supporting 90 percent of the airplane mass (keeping some load on the tires for directional control), the skid bearing pressure becomes 1034 kPa (150 psi) and the stopping distance is reduced to merely 0.91 km (3000 ft). Of course, in the latter example a much greater potential for runway surface damage exists because of the higher bearing pressure.

Figure 12 shows that the amount of skid material required to stop the airplane is essentially independent of the vertical loading on the skid or the stopping distance. In other words, a fixed mass or volume of wire is necessary to absorb a fixed amount of kinetic energy. The magnitude of this wear, as demonstrated by the data of figures 11 and 12, may preclude the practical application of skids for commercial aircraft use. Figures 11 and 12 show that approxi-

mately 68 kg (150 lbm) of the skid material is required to accomplish a landing which translates to 1.14 cm (0.45 in.) of 17-7 PH stainless steel, h.t., II wire 0.76 mm (0.030 in.) in diameter having a total contact area of 0.77 m^2 (1200 in^2). If it is assumed that the brush skid has an initial wire length of 5 cm (2 in.), then the mass of the wire alone for a new brush becomes 302 kg (655 lbm), and the brake is good for four landings only. Admittedly, 180 knots is a high brake-application speed. If the brakes were not applied until the airplane reached one-half that speed, the lifetime of the skid would be increased by a factor of 4. However, consideration must be given not only to the mass of the brush but also to the mass of its backing plate and the mechanisms, hydraulics, etc., necessary to operate the skid as a brake. In view of these masses and the short skid lifetimes, such a concept does not appear to be economically practical for general commercial applications. The concept may have considerable merit for spacecraft use, however, where the number of landings per brake is of secondary importance; thus, the skid could be limited to only that brush material necessary to satisfy one landing. A 90 720-kg (200 000-lbm) vehicle would require at least four conventional main gear wheels and brakes. Applying a conservative 45 kg (100 lbm) per brake would mean a total brake mass of 181 kg (400 lbm). The data of figures 11 and 12 suggest that 181 kg (400 lbm) might be ample for a one-landing brush in a wheel-skid gear capable of operating in all weather conditions.

CONCLUDING REMARKS

An experimental investigation was conducted to examine the friction and wear characteristics of 22 types and sizes of wires for potential use in wire-brush skids. The test procedure consisted of placing brushes fabricated from the wires on a belt sander under preselected bearing loads and monitoring the drag force and wear behavior. Data were obtained over distances up to 3048 m (10 000 ft) at bearing pressures of 172 to 1034 kPa (25 to 150 psi).

In general, the friction coefficient developed by the candidate wires was found to be independent of bearing pressure and ranged between 0.4 and 0.6 under the test conditions of this investigation. Of the materials examined, the heat-treated beryllium copper developed the highest friction level and the large diameter music wires the lowest. The friction coefficient was not degraded when the surface was wetted and appears to be independent of wire diameter except perhaps when wire size is relatively large compared with the surface roughness.

Of the wires tested, René 41 wire exhibited the best wear characteristics, whereas the heat-treated beryllium copper and the two wire ropes demonstrated the poorest. For all test wires, the wear was shown to increase with increasing bearing pressure and, in general, for the same bearing pressure, wear increased with increasing wire diameter and decreased when the surface was wetted.

Generally, hard materials provided greater wear resistance but at the expense of low friction and, correspondingly, the high friction demonstrated by the soft materials was accompanied by high wear rates. However, selecting a skid material for practical applications requires consideration of not only the skid wear and friction characteristics, but also such factors as runway surface damage (not addressed in this investigation) and material costs.

The concept of using wire-brush skids to supply the braking force in a wheel-skid gear concept appears to have considerable merit for spacecraft. In such an application, the brush would be replaced following each landing and landing operations could take place under all weather conditions.

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TABLE I.- WIRE AND TEST BRUSH PARAMETERS

[Brush initial trim length, 5.08 cm (2.00 in.)]

Wire type	Wire diameter		Wire density		Wires per brush	Total contact area	
	mm	in.	kg/m^3	lbm/in^3		mm^2	in^2
Music, carbon steel	0.33	0.013	7920	0.286	78	6.68	0.01035
	.56	.022	7920	.286	28	6.86	.01064
	.76	.030	7750	.280	14	6.38	.00990
	1.07	.042	7810	.282	7	6.26	.00970
	1.93	.076	7790	.281	2	5.85	.00907
	2.16	.085	7810	.282	1	3.66	.00567
René 41, w.w.	1.02	.040	8220	.297	8	6.48	.01005
Inconel X-750, hard	.89	.035	8500	.307	11	6.83	.01058
Inconel X-750, w.w., h.t.	.89	.035	8610	.311	12	7.45	.01154
A-286, h.t.	.76	.030	7970	.288	14	6.38	.00990
A-286, a.d.	.76	.030	8030	.290	14	6.38	.00990
Rocket wire, a.d.	.76	.030	7970	.288	14	6.38	.00990
17-7 PH stainless steel, h.t., I	.51	.020	7690	.278	33	6.69	.01037
17-7 PH stainless steel, h.t., II	.76	.030	7670	.277	14	6.38	.00990
17-7 PH stainless steel, a.d.	.76	.030	7750	.280	14	6.38	.00990
Wheel brush	.56	.022	7920	.286	13	3.19	.00494
AISI type 302 stainless steel, spring temper	.81	.032	7720	.279	13	6.74	.01045
17-4 PH stainless steel, w.w., h.t.	.89	.035	7970	.288	12	7.45	.01154
AISI type 347 stainless steel, w.w.	.89	.035	7830	.283	11	6.83	.01058
Beryllium copper, h.t.	.76	.030	8360	.302	14	6.38	.00990
Wire rope I	.25	.010	7030	.254	133	6.74	.01044
Wire rope II	.64	.025	7810	.282	19	6.02	.00933

TABLE II.- DESCRIPTION OF WIRES USED IN TEST BRUSHES

Wire type	Wire description
Music, carbon steel	Spring wire, Federal specification Q Q-W-470A-2
René 41, w.w.	Inert gas welding wire, AISI, no. 683
Inconel X-750, hard	Spring temper
Inconel X-750, w.w., h.t.	Welding wire heat treated to 1240 MPa (180 000 psi) tensile strength
A-286, h.t.	Spring wire heat treated to spring temper
A-286, a.d.	Spring wire as drawn
Rocket wire, a.d.	Carbon steel wire, minimum tensile strength 2650 MPa (385 000 psi)
17-7 PH stainless steel, h.t., I	Stainless steel wire heat treated to spring temper (Cond. "CH") by heating at 482° C (900° F) for 1 hr
17-7 PH stainless steel, h.t., II	
17-7 PH stainless steel, a.d.	Spring wire as drawn, nominal tensile strength of 1860 MPa (270 000 psi)
Wheel brush	Cleaning wheel brush wire, FSN 5130-293-1983
AISI type 302 stainless steel, spring temper	Federal specification Q Q-W-423
17-4 PH stainless steel, w.w., h.t.	Welding wire heat treated to 1380 MPa (200 000 psi) tensile strength
AISI type 347 stainless steel, w.w	Inert gas welding wire
Beryllium copper, h.t.	Tempered to 1090 MPa (158 000 psi) tensile strength
Wire rope I	7 by 19, 0.32-cm (0.125-in.) diameter wire rope
Wire rope II	One strand of 7 by 19 wire rope 0.95 cm (0.375 in.) in diameter

TABLE III.- AVERAGE FRICTION COEFFICIENTS FOR TEST BRUSHES

[Bearing pressure, 689 kPa (100 psi)]

Wire type	Wire diameter		Friction coefficient
	mm	in.	
Beryllium copper, h.t.	0.76	0.030	0.60
17-4 PH stainless steel, w.w., h.t.	.89	.035	.55
AISI type 347 stainless steel, w.w.	.89	.035	.53
A-286, a.d.	.76	.030	.53
Wire rope I	.25	.010	.52
17-7 PH stainless steel, h.t., II	.76	.030	.50
Inconel X-750, w.w., h.t.	.89	.035	.48
Music wire	.33	.013	.48
17-7 PH stainless steel, a.d.	.76	.030	.47
A-286, h.t.	.76	.030	.47
Music wire	.76	.030	.47
AISI type 302 stainless steel, spring temper	.81	.032	.46
17-7 PH stainless steel, h.t., I	.51	.020	.46
Wire rope II	.64	.025	.46
Music wire	.56	.022	.46
Rocket wire, a.d.	.76	.030	.46
Music wire	1.07	.042	.45
Inconel X-750, hard	.89	.035	.45
Wheel brush	.56	.022	.43
René 41	1.02	.040	.40
Music wire	2.16	.085	.37
Music wire	1.93	.076	.35

TABLE IV.- WEAR INDEX OF TEST BRUSHES

[Bearing pressure, 689 kPa (100 psi)]

Wire type	Wire diameter		Wear index	
	mm	in.	$\frac{cm^3}{cm^2}/m$	$\frac{in^3}{in^2}/ft$
René 41	1.02	0.040	5.25×10^{-4}	0.63×10^{-4}
Rocket wire, a.d.	.76	.030	5.83	.70
A-286, h.t.	.76	.030	6.00	.72
Inconel X-750, hard	.89	.035	6.25	.75
17-7 PH stainless steel, h.t., II	.76	.030	6.58	.79
17-7 PH stainless steel, h.t., I	.51	.020	7.00	.84
Inconel X-750, w.w., h.t.	.89	.035	7.08	.85
17-7 PH stainless steel, a.d.	.76	.030	7.33	.88
A-286, a.d.	.76	.030	7.41	.89
AISI type 302 stainless steel, spring temper	.81	.032	9.42	1.13
Music wire	.33	.013	10.00	1.20
AISI type 347 stainless steel, w.w.	.89	.035	10.42	1.25
Wheel brush	.56	.022	10.50	1.26
Music wire	.56	.022	10.50	1.26
Music wire	.76	.030	12.00	1.44
17-4 PH stainless steel, w.w., h.t.	.89	.035	15.50	1.86
Music wire	1.07	.042	16.08	1.93
Music wire	1.93	.076	17.75	2.13
Music wire	2.16	.085	18.92	2.27
Beryllium copper, h.t.	.76	.030	29.17	3.50
Wire rope II	.64	.025	31.00	3.72
Wire rope I	.25	.010	35.42	4.25

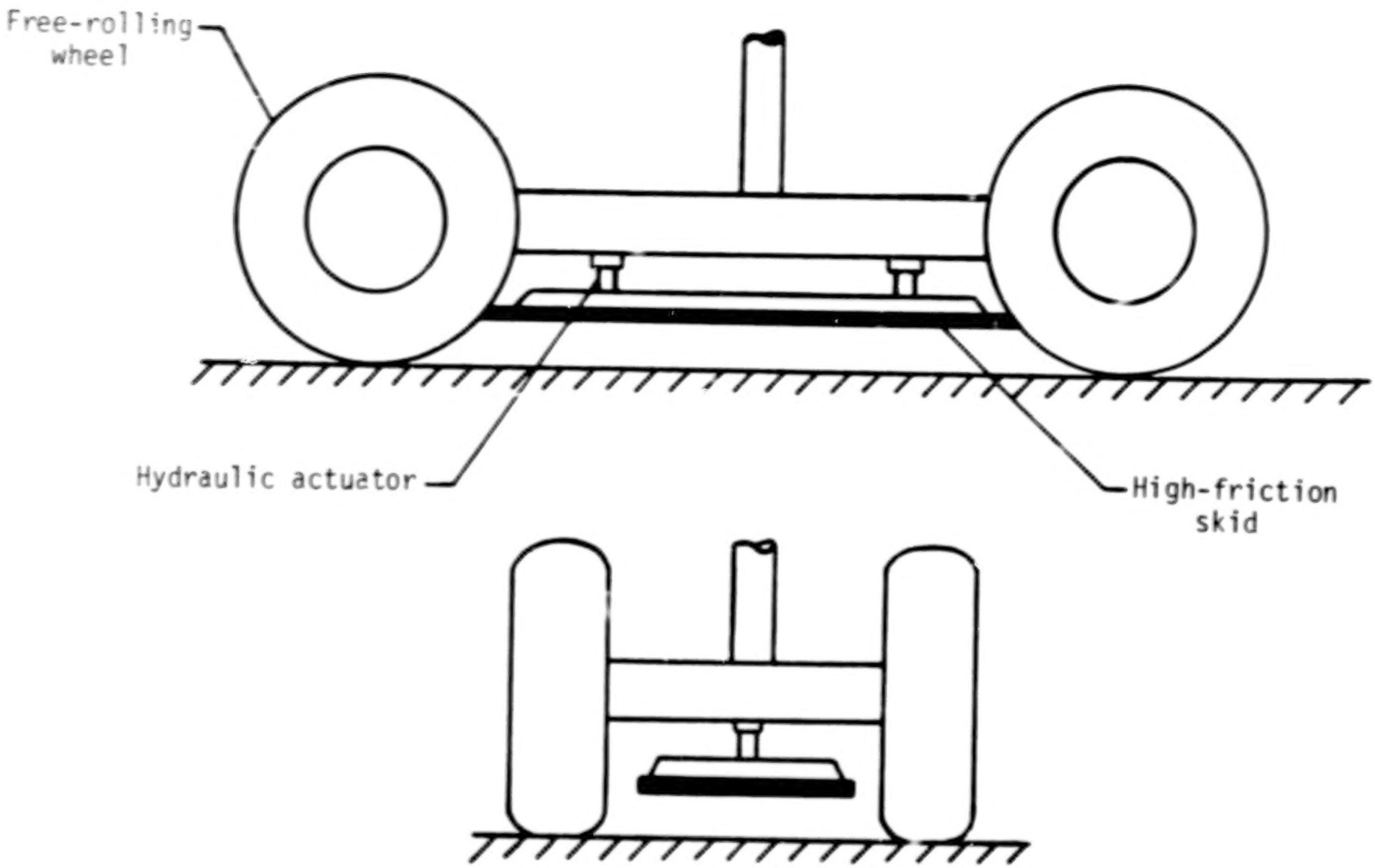
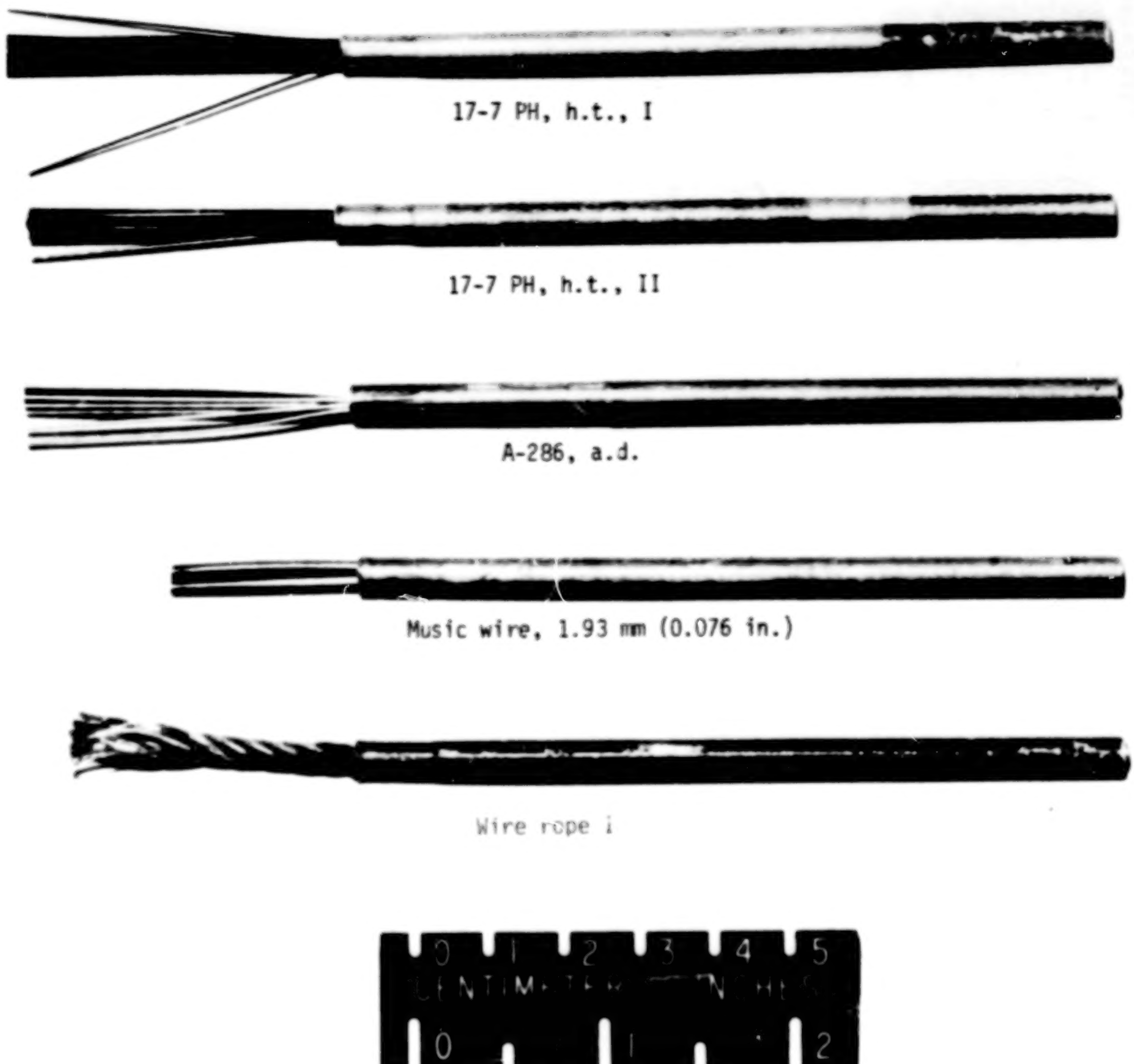


Figure 1.- Wheel and skid landing-gear system.



L-77-3349.1

Figure 2.- Photograph of several brushes after tests.

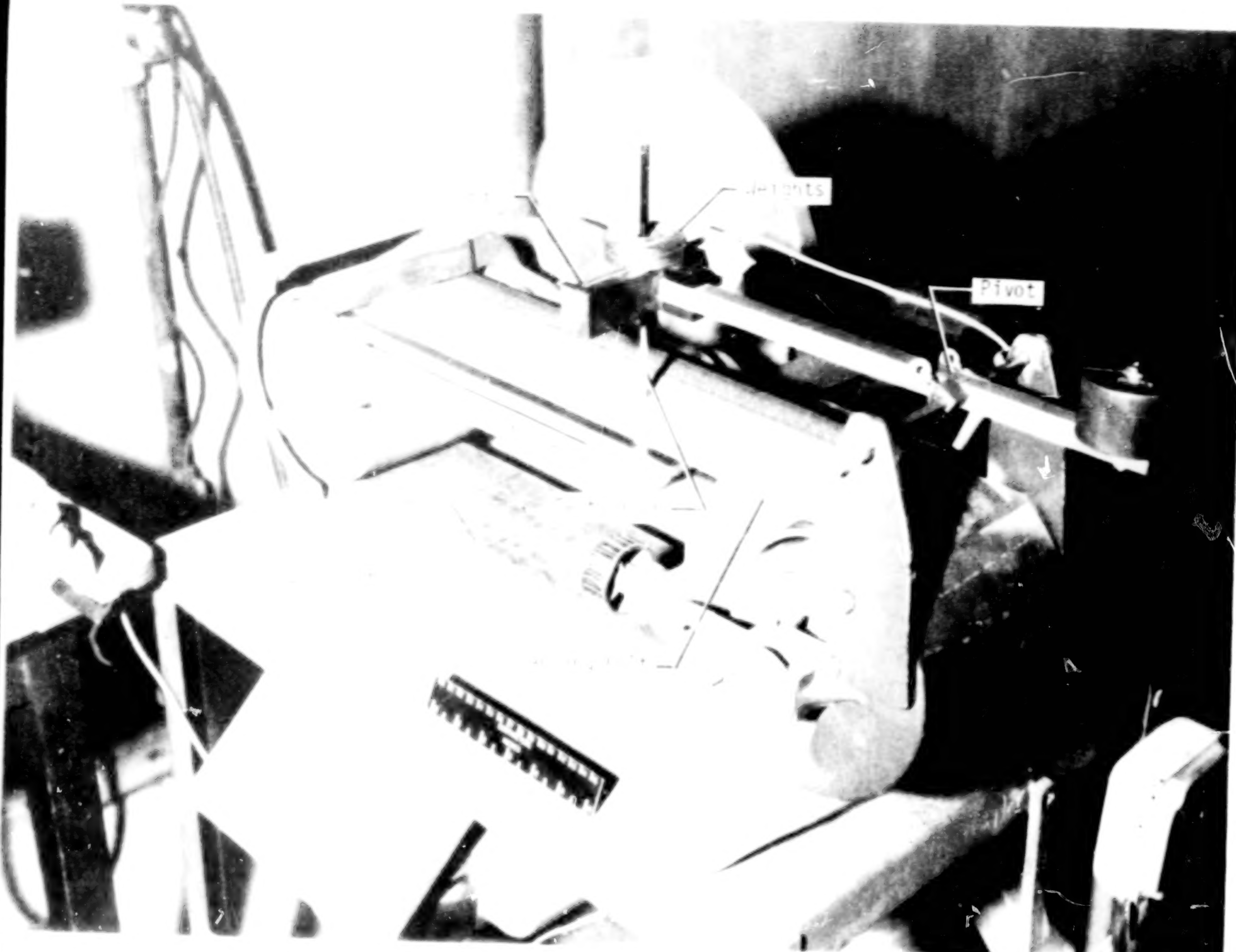


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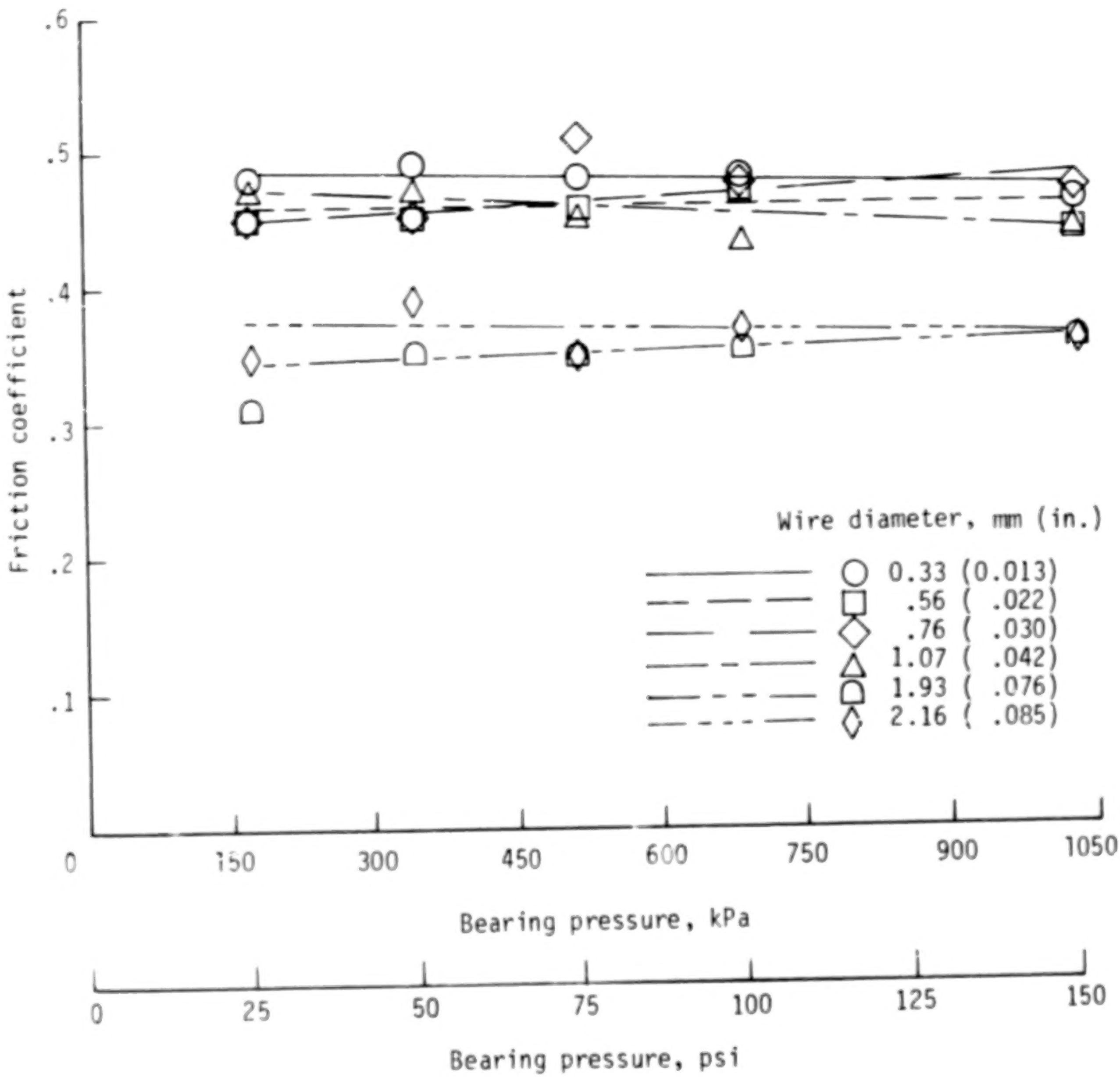
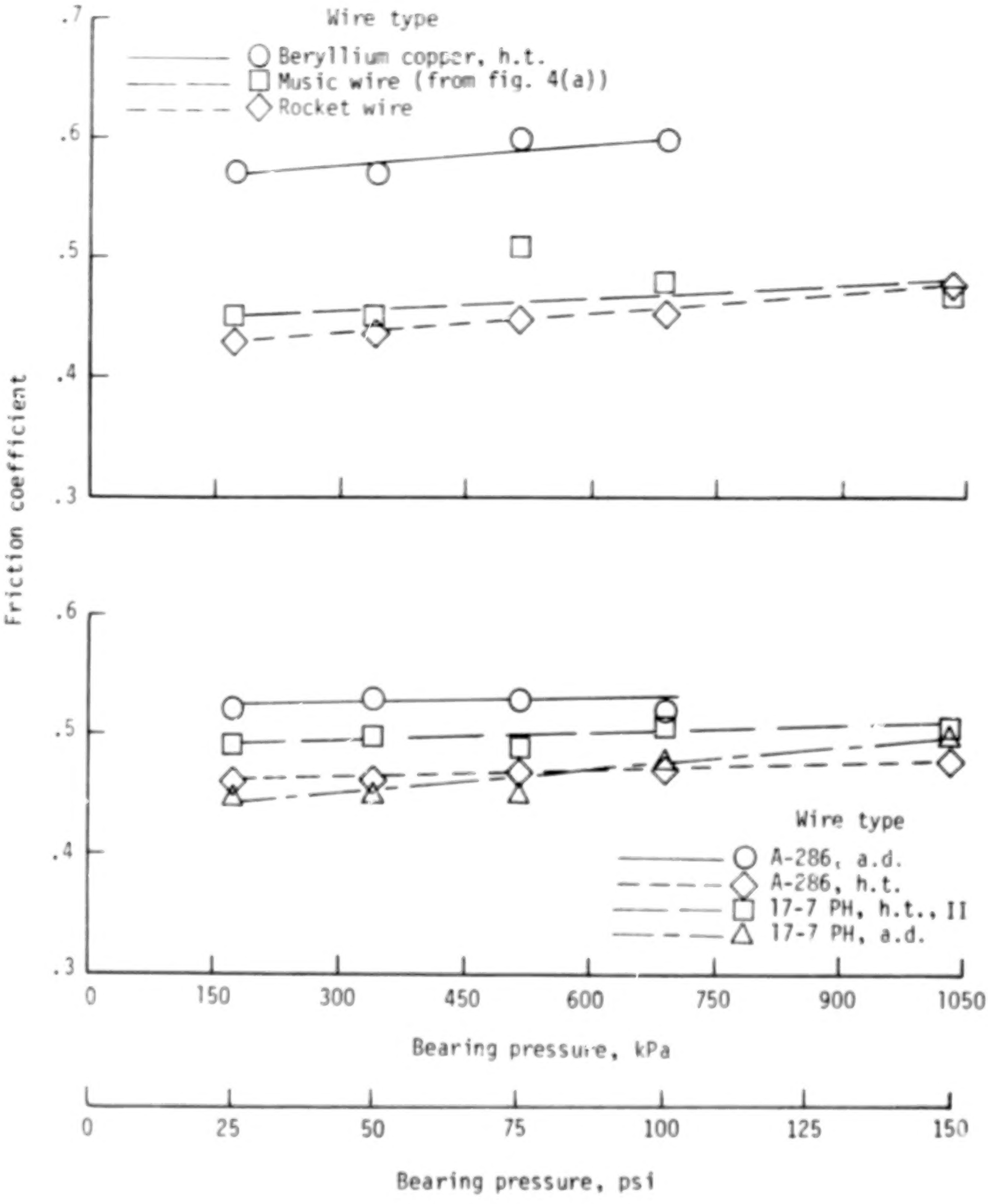
Figure 3.- Test apparatus used in investigation.



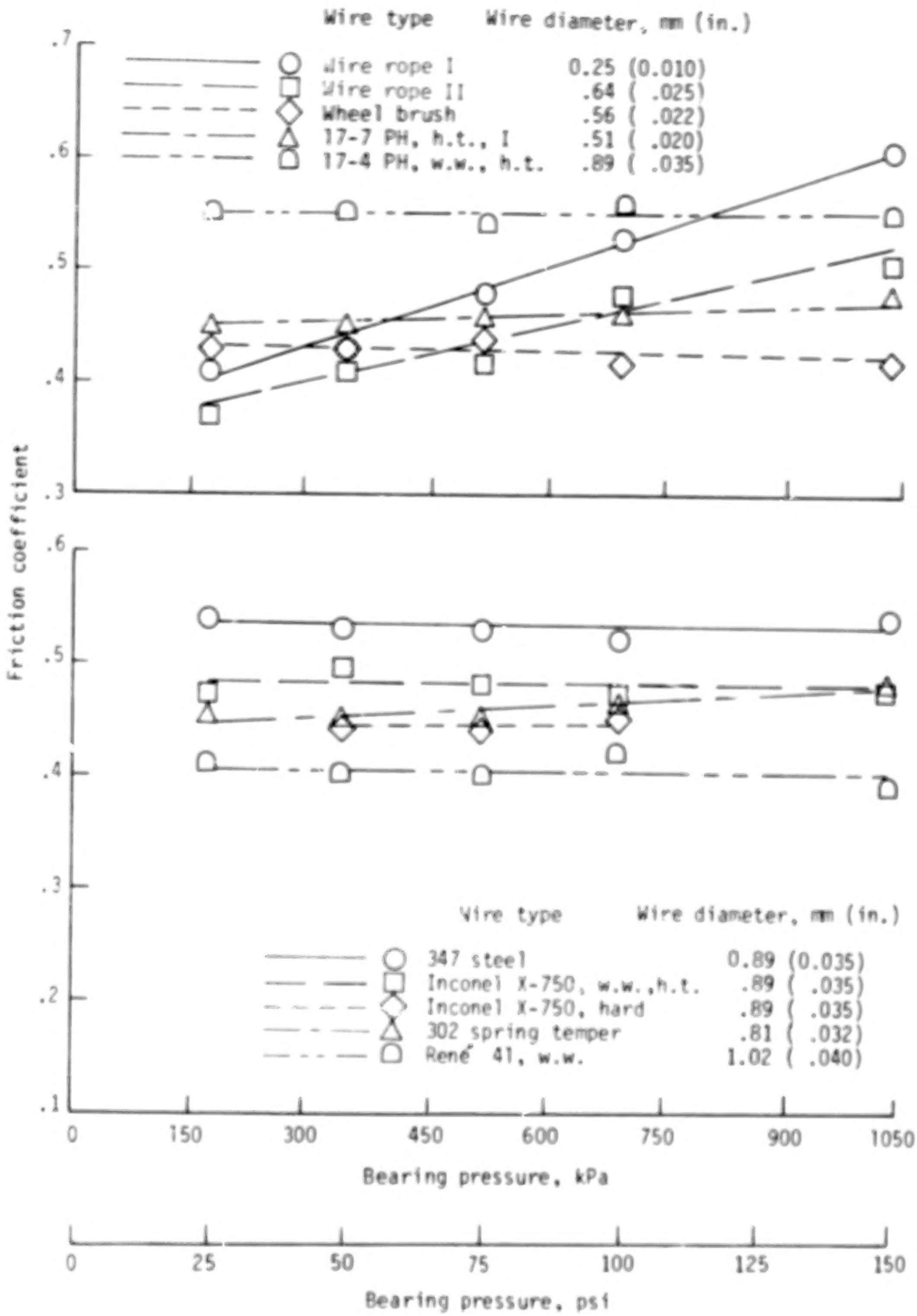
(a) Brushes fabricated from music wire.

Figure 4.- Variation of friction coefficient with bearing pressure for test brushes.



(b) Brushes fabricated from 0.76-mm (0.030-in.) diameter wire.

Figure 4.- Continued.



(c) Brushes fabricated from wires of various diameters.

Figure 4.- Concluded.

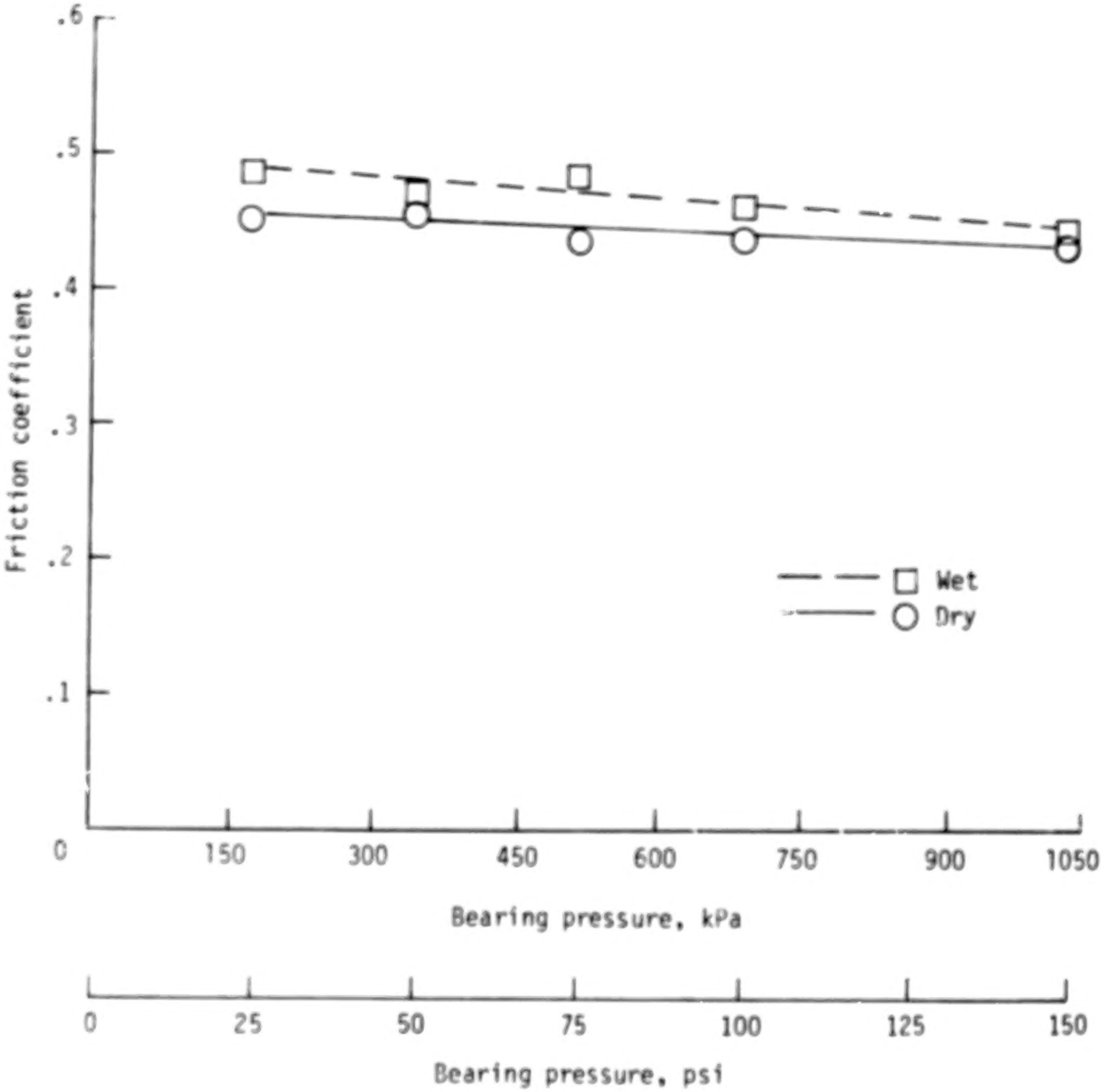


Figure 5.- Variation of friction coefficient with bearing pressure on wet and dry surfaces. Wire type: 17-7 PH stainless steel, h.t., II, 0.76 mm (0.030 in.) in diameter.

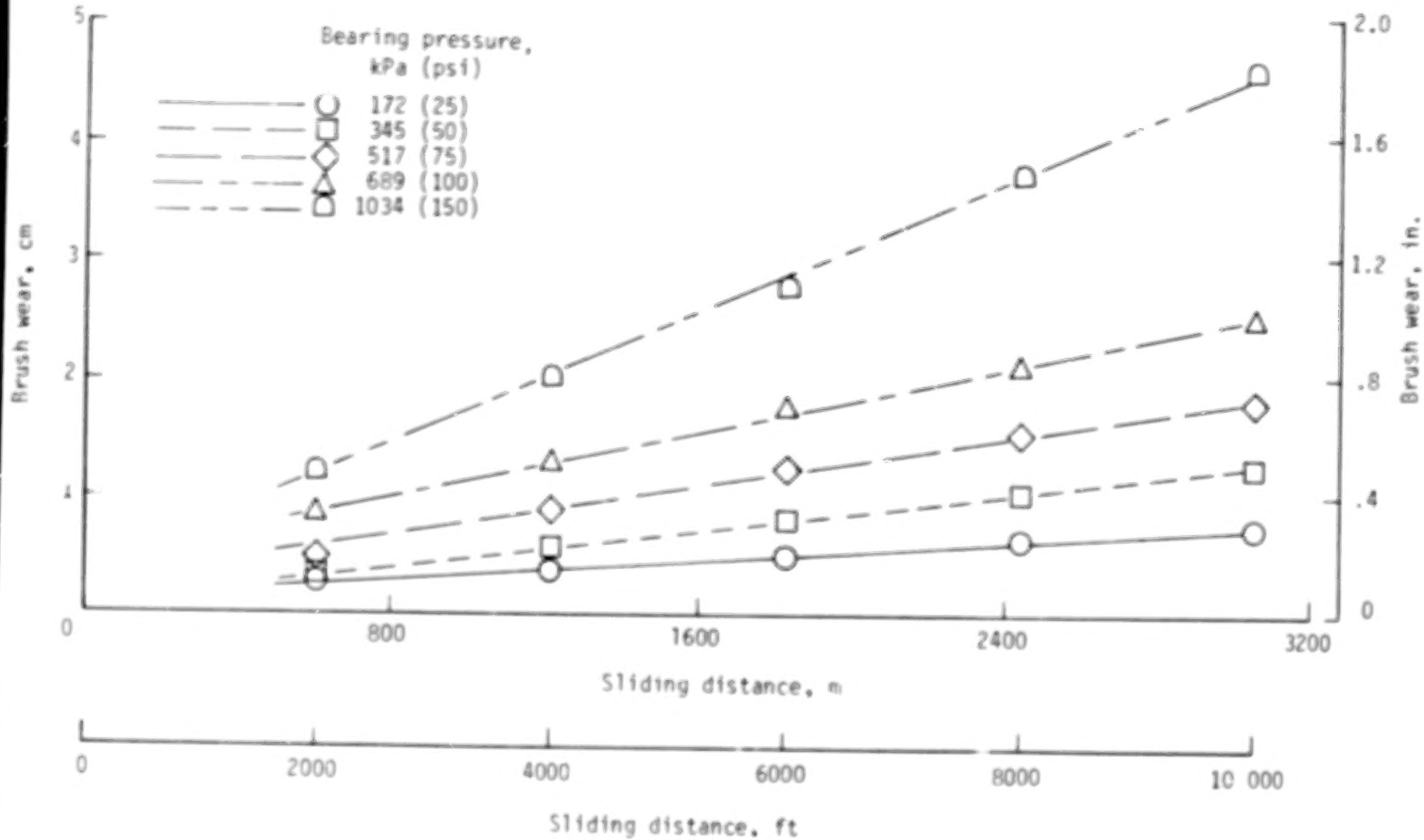


Figure 6.- Typical variation of brush wear with sliding distance. Wire type: 17-7 PH stainless steel, h.t., II, 0.76 mm (0.030 in.) in diameter.

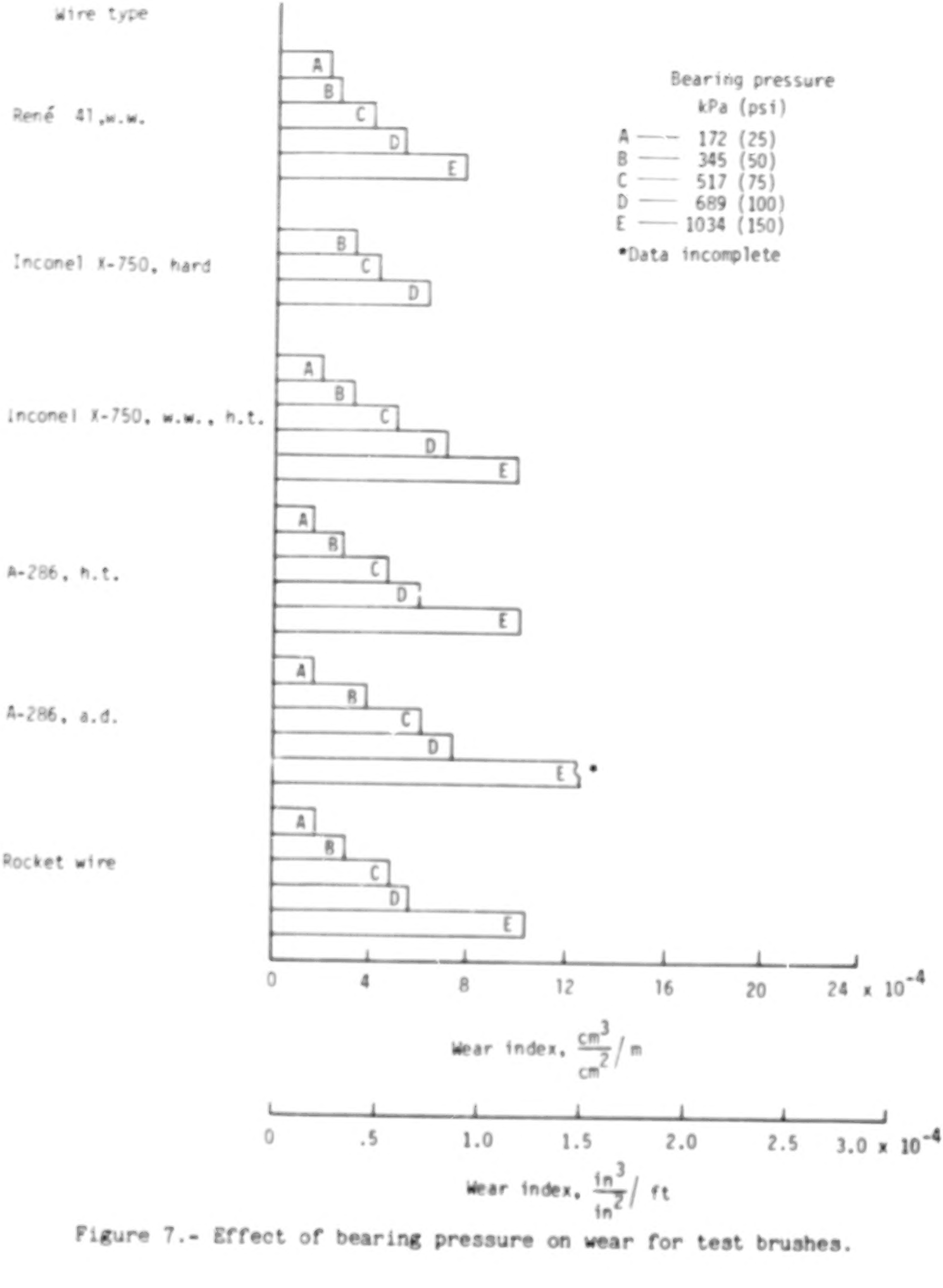


Figure 7.- Effect of bearing pressure on wear for test brushes.

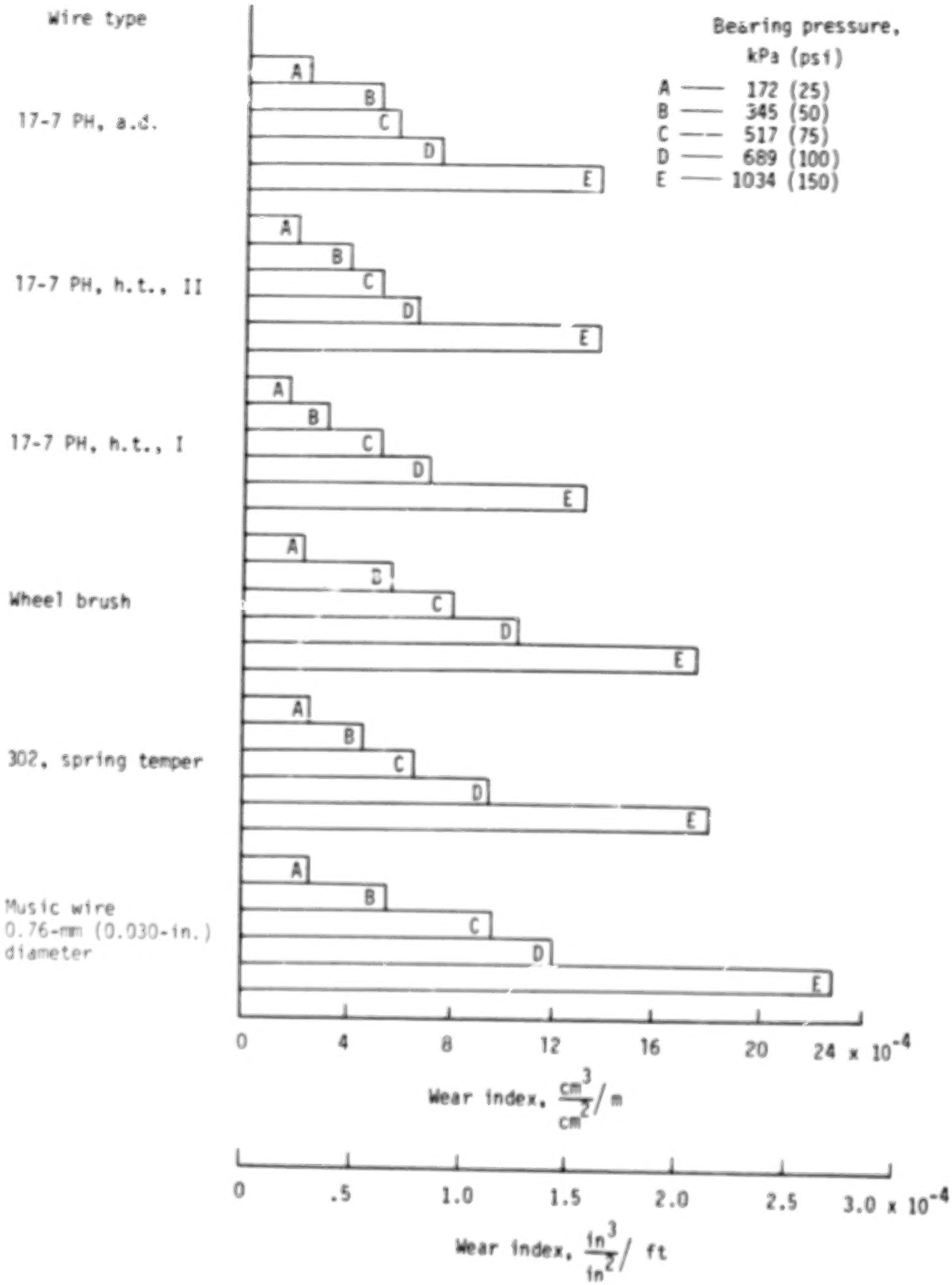


Figure 7.- Continued.

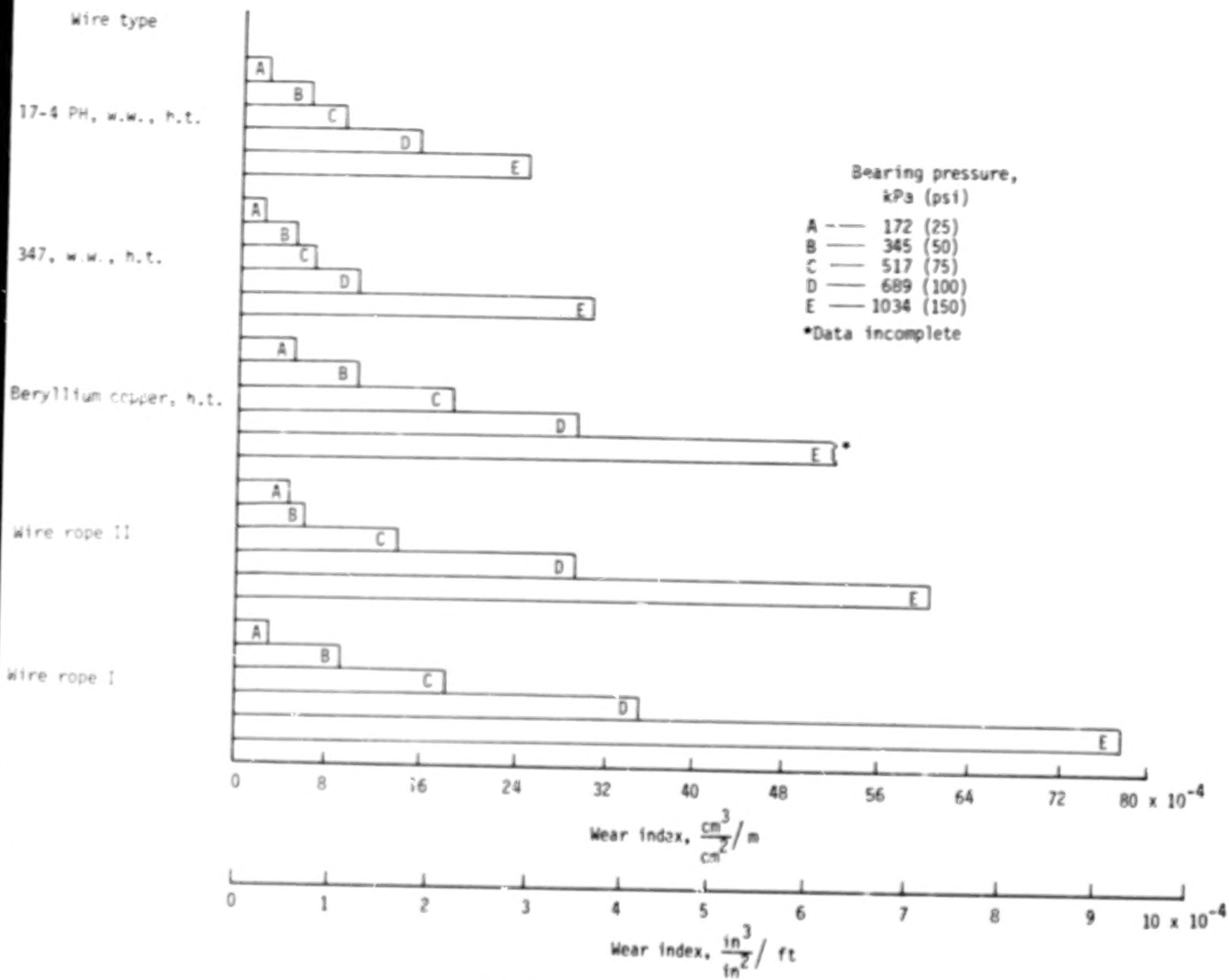


Figure 7.- Concluded.

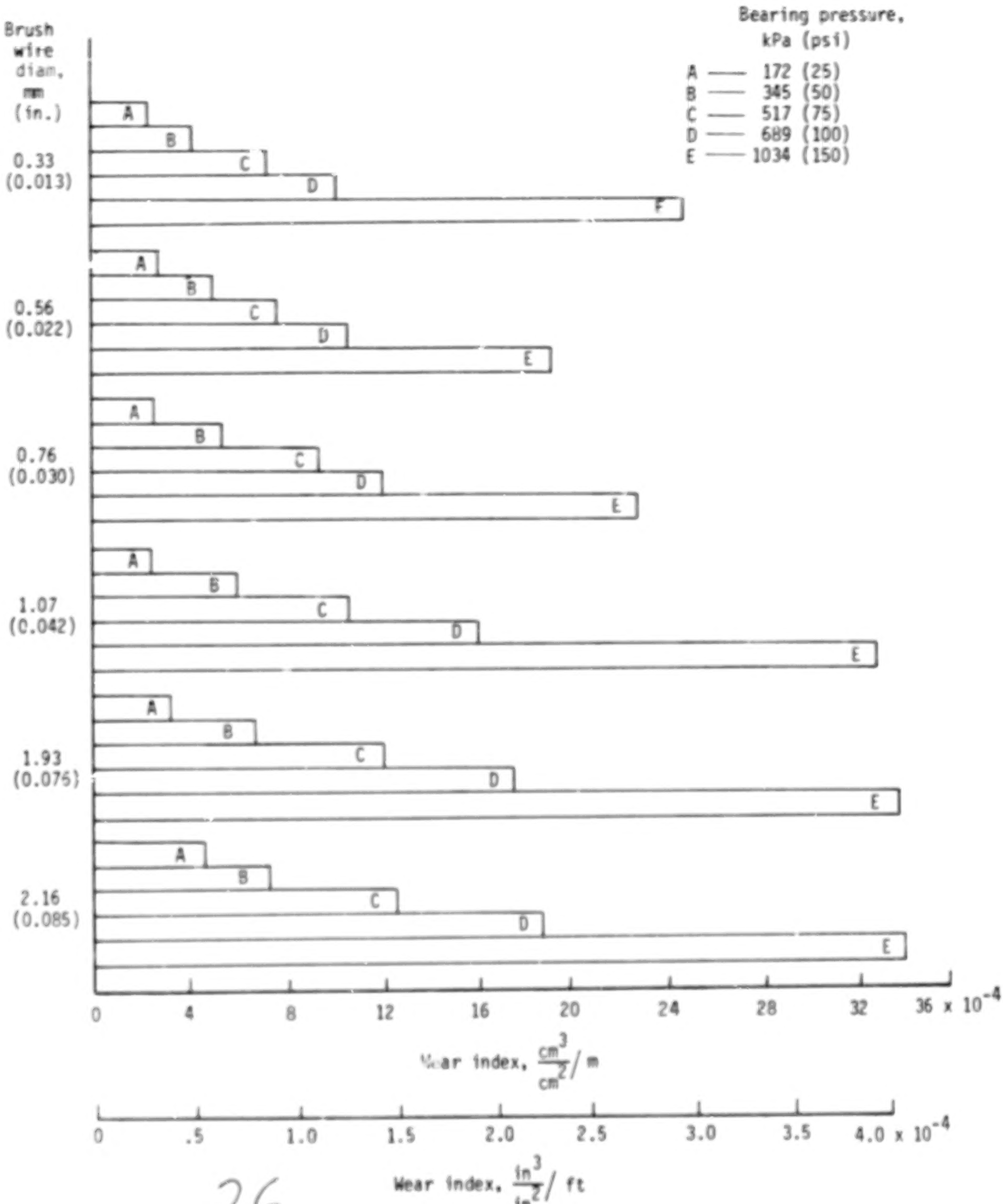


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Figure 8.- Effect of wire diameter on wear for music wire brushes at various bearing pressures.

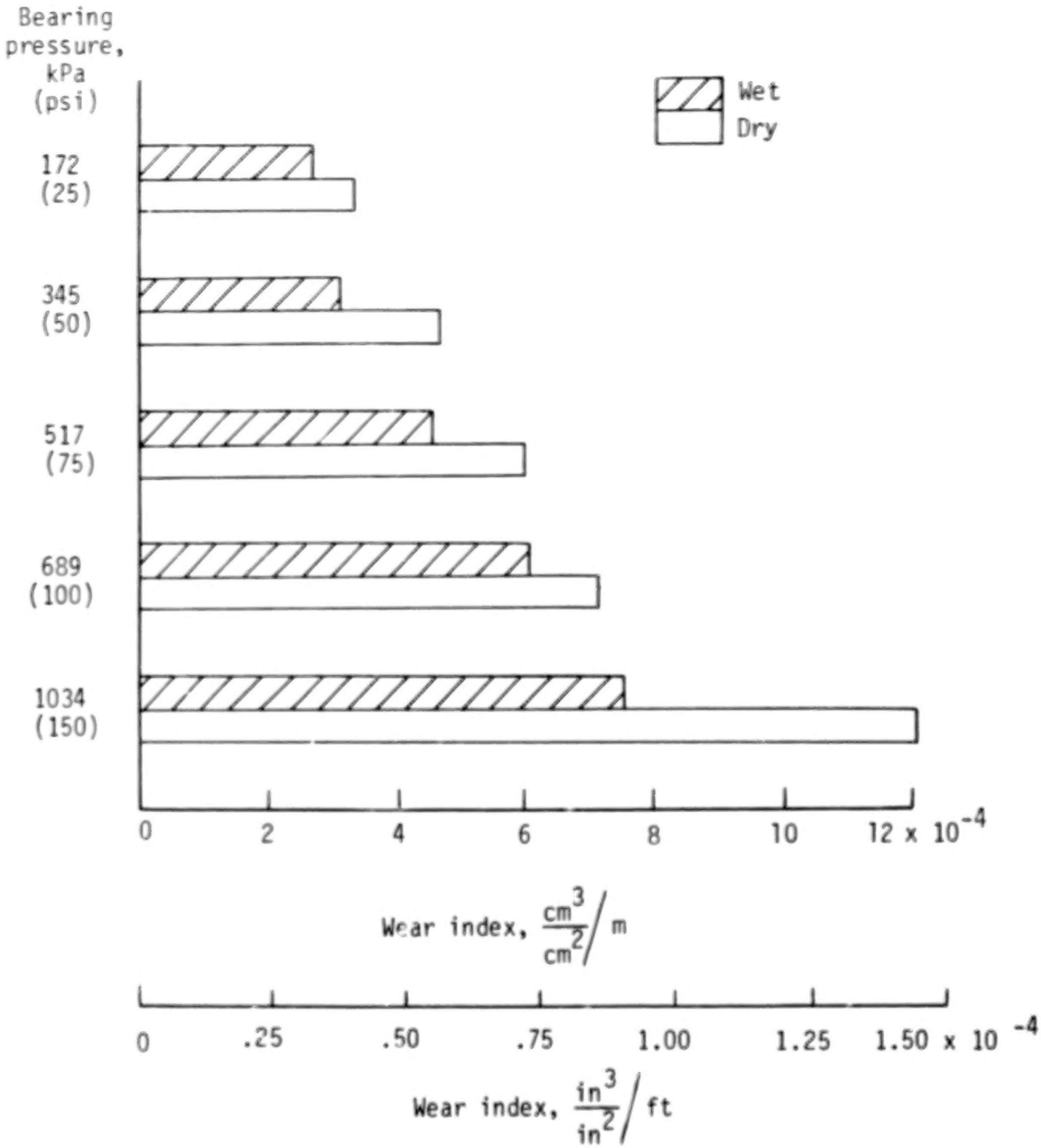

Figure 9.- Effect of surface wetness on wear for 17-7 PH stainless steel, h.t., II wire 0.76 mm (0.030 in.) in diameter at various bearing pressures.

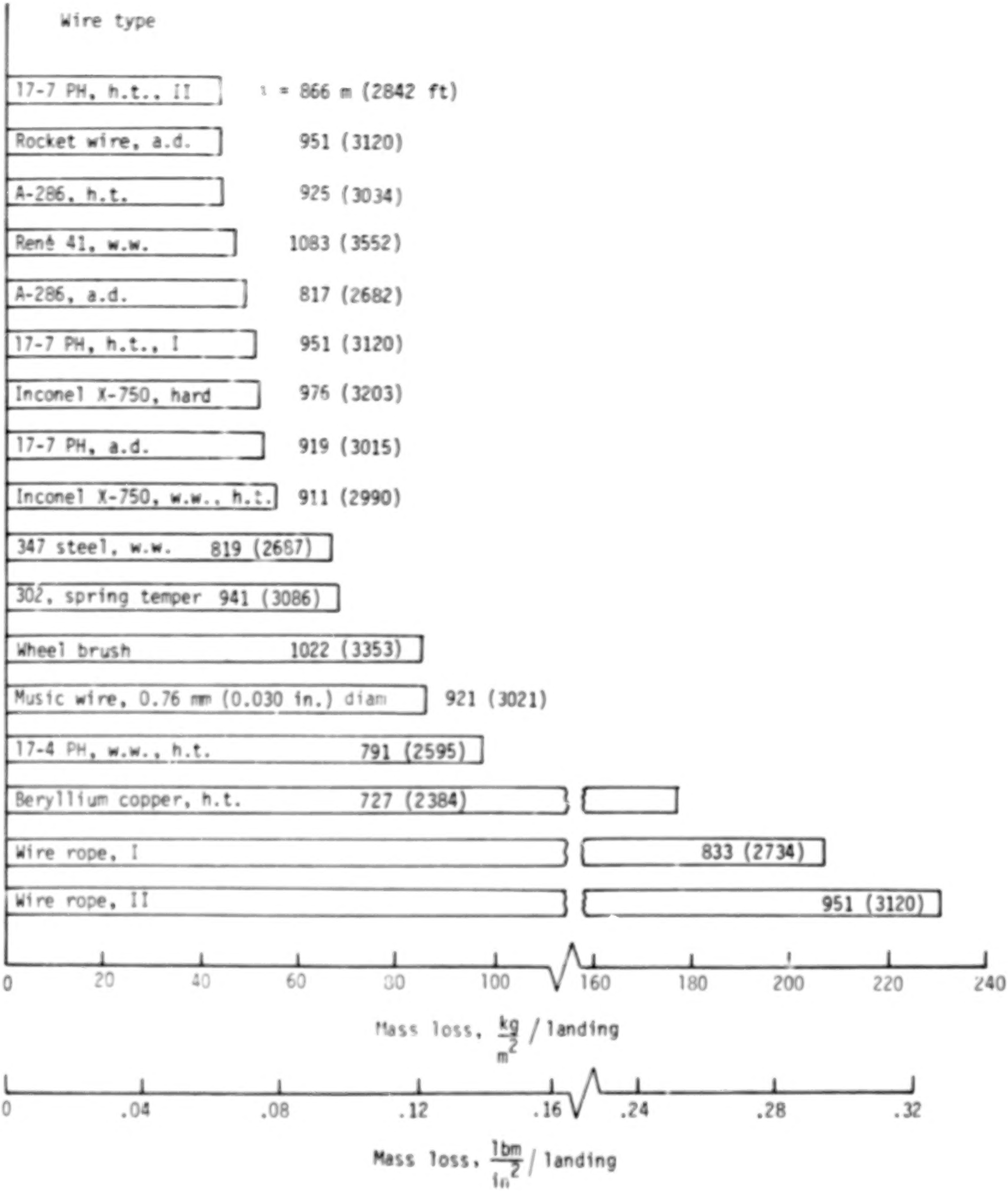

Figure 10.- Calculated wear and stopping distance expected of various wire types if used in skids to stop an airplane having an initial ground speed of 180 knots (bearing pressure, 689 kPa (100 psi)).

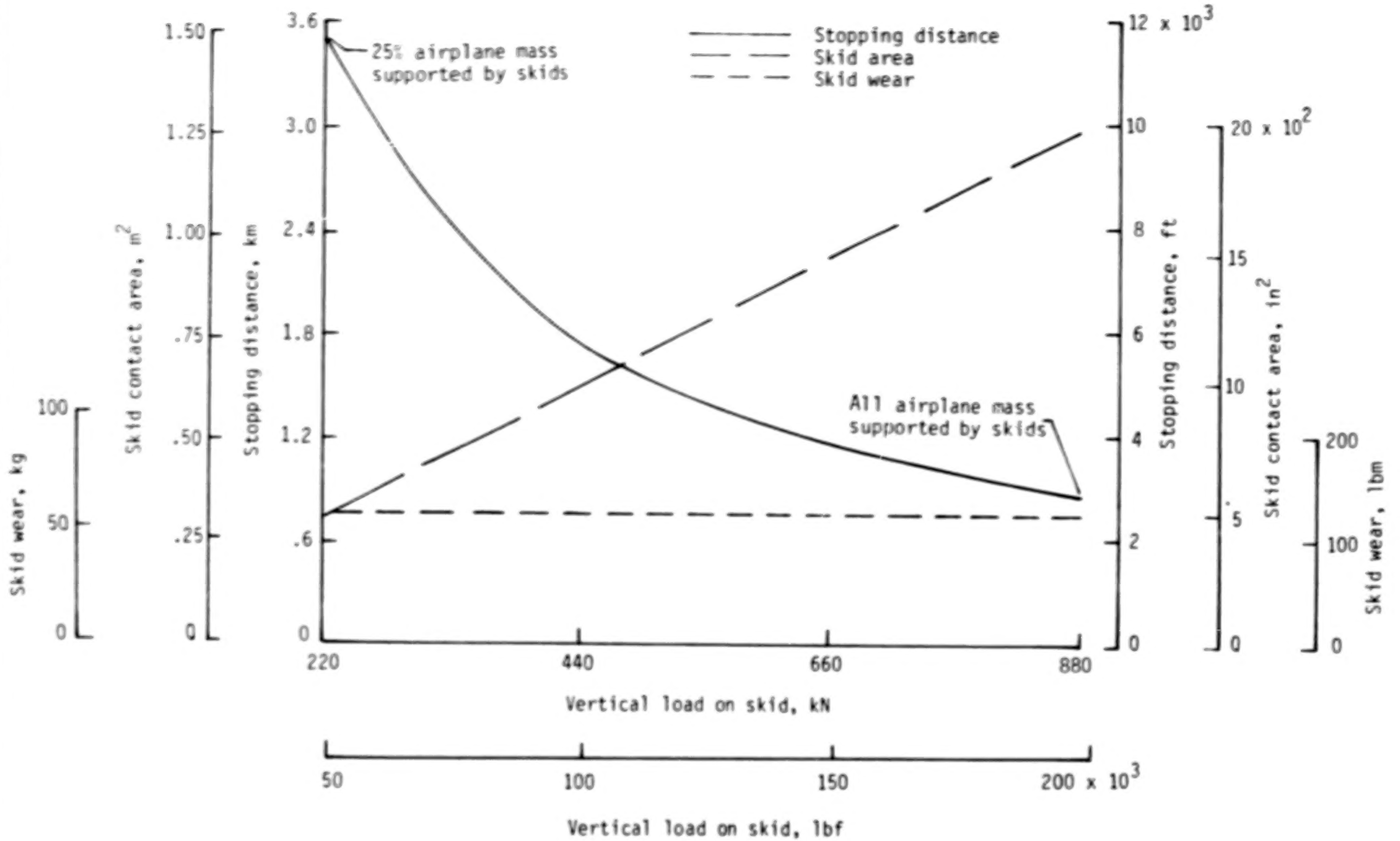

Figure 11.- Calculated stopping distance, wear, and skid contact area at various skid loadings required to stop 90 720-kg (200 000-lbm) airplane landing at 180 knots equipped with skid(s) fabricated with 17-7 PH stainless steel, h.t., II wire 0.76 mm (0.030 in.) in diameter loaded to 689 kPa (100 psi).

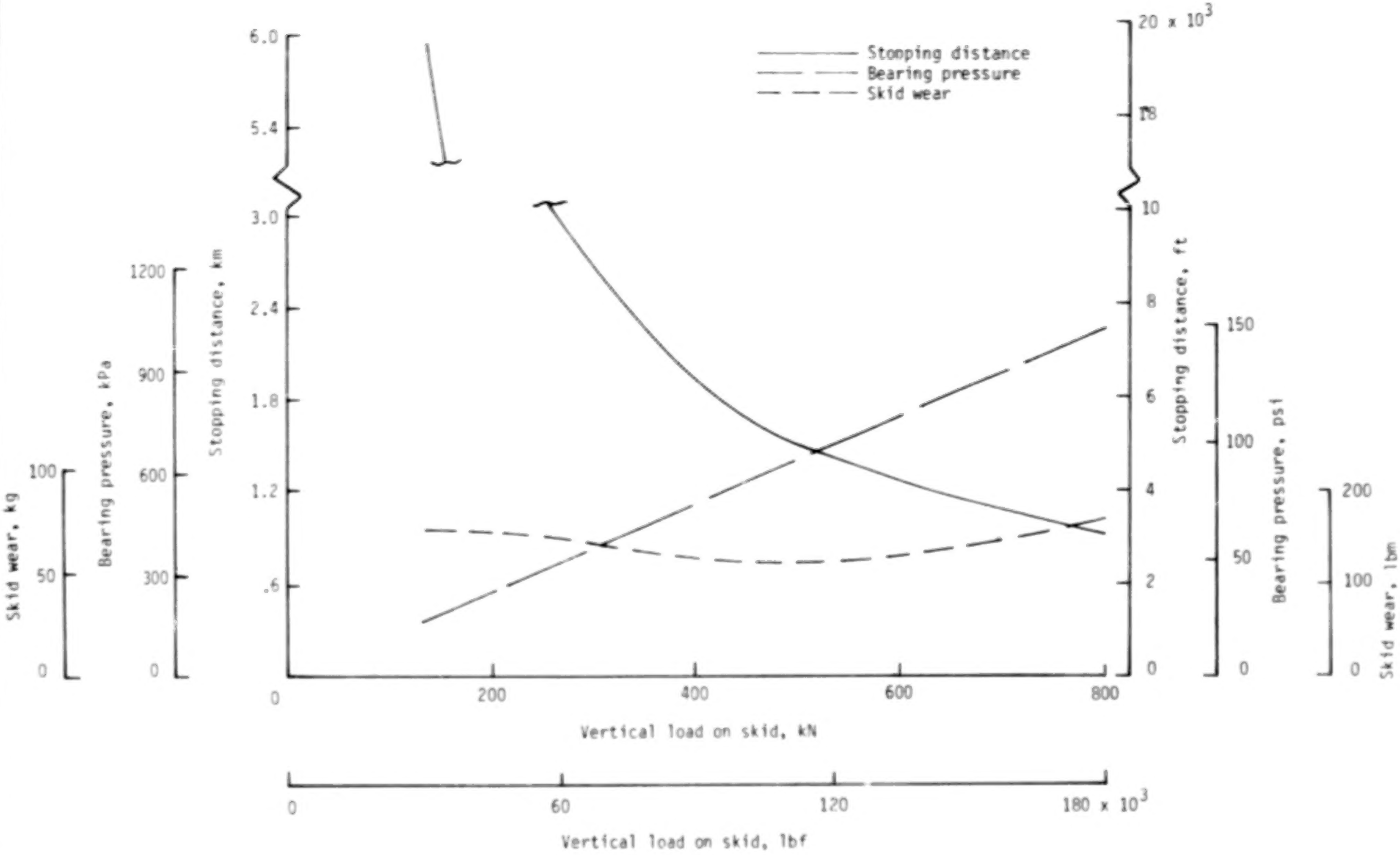

Figure 12.- Calculated stopping distance, wear, and bearing pressure at various skid loadings for 90 720-kg (200 000-lbm) airplane landing at 180 knots equipped with 0.77-m^2 (1200-in^2) skid fabricated with 17-7 PH stainless steel, h.t., II wire 0.76 mm (0.030 in.) in diameter.

90

50

END

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